PB86-171600

Influence of Breathing Mode and Activity Level on the Regional Deposition of Inhaled Particles and Implications for Regulatory Standards (March 1986)

(U.S.) Health Effects Research Lab.
Research Triangle Park, NC

Mar 86

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA/600/D-86/055	2.
3. RECIPIENT'S ACCESSION NO. PB86-171600/AS	
4. TITLE AND SUBTITLE INFLUENCE OF BREATHING MODE AND ACTIVITY LEVEL ON THE REGIONAL DEPOSITION OF INHALED PARTICLES AND IMPLICATIONS FOR REGULATORY STANDARDS	5. REPORT DATE March 1986 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) F. Miller,[1] T.B. Martonen,[1] M.G. Menache[2] M. Lippmann[3], R.C. Graham,[2] D. M. Spektor,[3]	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS [1]HERL, Environmental Protection Agnecy, Fesearch Triangle Park, NC 27711, [2]Northrop Services, Inc., Research Triangle Park, NC 27709, [3]New York Univ. Med. Ctr., New York, NY 10016, USA.	10. PROGRAM ELEMENT NO. AAGA1D 11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Office of Research & Development Health Effects Research Laboratory USEPA Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED 14. SPONSORING AGENCY CODE EPA-600/11
15. SUPPLEMENTARY NOTES	

16. ABSTRACT

Particulate size-selective sampling is an important consideration in determining ambient air quality standards and threshold limit values for workplace exposures. Hazard evaluations, as well as risk analyses, can benefit from an improved understanding of factors affecting regional respiratory tract deposition of particles in man. Here, thoracic deposition and its component parts are examined, as a function of particulate size, for ventilation rates ranging from normal respiration to heavy exercise in individuals who are habitual mouth breathers and in those who normally employ oronasal breathing when minute ventilations exceed approximately 35 $Lmin^{-1}$. Nonlinear regression techniques were used to fit logistic models of the form $Y = [1 + e^{\alpha + \beta \log X}]^{-1}$ to data from tests measuring extrathoracic (ET) and tracheobronchial (TB) deposition. X was defined as an impaction parameter ($\rho d^2 Q$) and as the aerodynamic diameter of the particle (D_{ae}) for ET and TB deposition, respectively. The logistic models yielded significantly improved fits of the experimental data compared to previously used linear regression models. Our analyses demonstrate that the activity level of the exposed population should be taken into account to assess the potential health consequences from ambient or workplace exposures.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 18
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

PB86-171600

EPA/600/D-86/055
March 1986

INFLUENCE OF BREATHING MODE AND ACTIVITY LEVEL ON THE REGIONAL DEPOSITION OF INHALED PARTICLES AND IMPLICATIONS FOR REGULATOR STANDARDS

by

F. J. Miller,* T. B. Martonen,* M. G. Menache,**
R. C. Graham,** D. M. Spektor, *** and M. Lippman***

*Health Effects Research Laboratory, USEPA
Research Triangle Park, NC 27711
**Northrop Services, Inc.,
Research Triangle Park, NC 27709
***New York University Medical Center,
New York, NY 10016

EPA Project Officer
F. J. Miller

HEALTH EFFECTS RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

INFLUENCE OF BREATHING MODE AND ACTIVITY LEVEL ON THE REGIONAL DEPOSITION OF INHALED PARTICLES AND IMPLICATIONS FOR REGULATORY STANDARDS

F.J. Miller,[1] T.B. Martonen,[1] M.G. Ménache,[2]
R.C. Graham,[2] D.M. Spektor,[3] and M. Lippmann[3]

[1]Health Effects Research Laboratory, Environmental Protection Agency, Research Triangle Park, NC 27711.
[2]Northop Services, Inc., Research Triangle Park, NC 27709
[3]New York University Medical Center, New York, NY 10016 USA.

Abstract Particulate size-selective sampling is an important consideration in determining ambient air quality standards and threshold limit values for workplace exposures. Hazard evaluations, as well as risk analyses, can benefit from an improved understanding of factors affecting regional respiratory tract deposition of particles in man. Here, thoracic deposition and its component parts are examined, as a function of particulate size, for ventilation rates ranging from normal respiration to heavy exercise in individuals who are habitual mouth breathers and in those who normally employ oronasal breathing when minute ventilations exceed approximately 35 $Lmin^{-1}$. Nonlinear regression techniques were used to fit logistic models of the form $Y = [1 + e^{\alpha + \beta \log X}]^{-1}$ to data from tests measuring extrathoracic (ET) and tracheobronchial (TB) deposition. X was defined as an impaction parameter ($\rho d^2 Q$) and as the aerodynamic diameter of the particle (D_{ae}) for ET and TB deposition, respectively. The logistic models yielded significantly improved fits of the experimental data compared to previously used linear regression models. Our analyses demonstrate that the activity level of the exposed population should be taken into account to assess the potential health consequences from ambient or workplace exposures.

Introduction Because the potential of atmospheric aerosols to affect health adversely is a function of mass median aerodynamic diameter (MMAD), hazard evaluation requires size-selective sampling of ambient contaminants. Therefore, determination of the size of particles that penetrate oro- and nasopharyngeal airways to reach tracheobronchial (TB) and pulmonary (P) regions and pose a potential threat to human health is of importance. Over the past thirty years, there have been numerous experimental studies of total and regional respiratory tract deposition of insoluble particles in man, with major reviews by LIPPMANN (1977) and the EPA (1982). Both spontaneous and controlled breathing patterns have been used with airflow rates ranging from normal respiration to heavy exercise with either nasal or oral breathing. SWIFT and PROCTOR (1982) used the data of YU et al. (1981) and CHAN and LIPPMANN (1980) in analyses that addressed deposition with oronasal breathing. In the current study, published data from various

laboratories for extrathoracic (ET) and TB deposition, along with previously unpublished data of LIPPMANN and co-workers at New York University (NYU), were fit to logistic regression models prior to examining the influence of breathing mode and activity level on TB, P, and thoracic deposition. Aggregation of deposition data in this manner is particularly relevant for regulatory applications where "population averages" are of more interest than are individual subject or specific (i.e., controlled vs. spontaneous) breathing pattern data.

Statistical Analysis Methods Using the digitized data of Fig. 1 in YU et al. (1981) and the recent data of HEYDER (1984), particulate losses in the ET region during nasal inspiration were examined with a logistic regression model of the form:

$$Y = [1 + e^{\alpha + \beta \log (\rho d^2 Q)}]^{-1} \qquad (1)$$

where ρ is the particle mass density (gcm^{-3}), d is the geometric particulate diameter (μm), and Q is the airflow rate ($cm^3 sec^{-1}$). The term $\rho d^2 Q$ defines an impaction parameter and has been found to be useful in characterizing the deposition of particles when inertial impaction is the dominant deposition mechanism. Of the nasal deposition studies contained in Fig. 1 in YU et al. (1981), only LIPPMANN (1970) included laryngeal losses in the ET region. To achieve a uniformly defined data base for nasal inspiration, the LIPPMANN (1970) data were not used in our analyses. Also, we excluded laryngeal losses reported by HEYDER (1984) prior to analyzing ET deposition with nasal inspiration.

Nonlinear regression estimation techniques were used to fit Eq. (1). The use of a logistic model and nonlinear estimation has the advantage that no "breakpoint" for a series of linear regressions need be assumed. Also, the predicted deposition efficiency will asymptotically approach a lower

bound of zero and an upper bound of one. Inspiratory mean deposition efficiency for mouth breathing was estimated in a similar manner using the data of HEYDER (1984), the new NYU data, and the digitized data of Fig. 3 from YU et al. (1981), excluding the FOORD et al. (1978) data. This resulted in an ET analysis for oral inspiration based upon deposition experiments which included the removal of particles by the larynx.

To enable comparisons between controlled and spontaneous breathing patterns, separate regression analyses were performed on the TB data of LIPPMANN (1977), CHAN and LIPPMANN (1980), and HEYDER (1984). An additional analysis involved combining all of the data of these investigators with new data from NYU. The recent NYU experiments contain deposition data for particles with $D_{ae} > 7$ μm, thereby adding new information on the deposition of larger particles. Regression analyses for TB deposition data, normalized to particles entering the trachea, utilized a logistic model based upon log D_{ae} rather than an impaction parameter. This is because TB deposition is due primarily to inertial impaction in the upper airways and to sedimentation in the lower airways. Effects of the sedimentation mechanism on TB deposition, in general, increase as Q decreases because of increased particulate residence times in bronchial airways. A more complicated parametric analysis involving both D_{ae} and Q might yield improvements over the 96% explanation of variation (see Results and Discussion) we obtained using only D_{ae} to fit the combined data of the NYU and Gesellschaft für Strahlen-und Umweltforschung m.b.H. (Frankfurt, FRG) laboratories that involved different breathing patterns and flow rates. This will be the subject of a future research effort; the focus here is to examine some trends in average deposition values across a widely varying population during oronasal breathing.

Unlike laboratory ET deposition data, the TB data are not evenly distributed across the range of particulate sizes of interest; thus, a weighted nonlinear regression was used. Weights that were a function of the reciprocal of the frequency of observations in a size interval by laboratory allowed size intervals to contribute more uniformly to the overall regression without masking the dispersion present in the data within a given interval.

The data of NIINIMAA et al. (1981) were used to determine the proportionality of airflow between the nose and mouth as a function of activity level. Subjects who normally use oronasal breathing to augment respiratory airflow (normal augmenters) when minute ventilation ($\dot{V}_E$) exceeds about 35 $Lmin^{-1}$, have 45-53% of inhaled air pass nasally. In subjects who habitually breathe oronasally, hereafter referred to as mouth breathers, the nasal fraction of airflow is considerably less than that for normal augmenters at any given $\dot{V}_E$ (see Table 1).

Since the logistic curve was fit to TB deposition data expressed as a percentage of particles entering the trachea, the TB data were converted to absolute deposition fractions when thoracic deposition was examined. The P portion of thoracic deposition was based upon the theoretical model of MARTONEN AND MILLER (in press) which calculates deposition in the ET, TB and P airways during a complete breathing cycle consisting of inspiration, pause, and expiration. Since the aerosol mass actually penetrating to the P compartment during inspiration is related to the filtering efficiencies of upstream (ET and TB) portions of the respiratory tract and is, therefore, a function of the portal of entry (i.e., nose or mouth) and flow rate into the body via the ET compartment, P deposition was computed in a manner to be consistent with the airflow proportionalities given in Table 1 for the various minute ventilations studied.

Results and Discussion After the ET data for nasal and oral inspiration contained in Figs. 1 and 3, respectively, of YU et al. (1981) were digitized, linear regressions were refit; the coefficients obtained were essentially the same as those proposed by the authors. The percentage of variation in the data explained by the linear model, R^2, was obtained during these reanalyses and found to be 68% for nasal inspiration and 46% for inspiration through the mouth. Excluding the data of LIPPMANN (1970) and FOORD ET AL. (1978) from the data points contained in Figures 1 and 3 of YU ET AL. (1981) had no impact on the linear regression analysis for nasal inspiration and only improved the R^2 by 8% for oral inspiration. When logistic models were fit to the ET data used in our analyses, significantly improved fits were obtained for nasal and oral inspiration, as evidenced by analogous overall R^2 values of 90% and 79%, respectively. Logistic model parameters for Eq. (1) for ET deposition were $\alpha = 7.13$ and $\beta = 1.96$ with nasal inspiration and $\alpha = 8.78$ and $\beta = 1.87$ with oral inspiration.

When separate logistic models based upon D_{ae} were fit to TB deposition data from investigators using spontaneous breathing (LIPPMANN, 1977; CHAN and LIPPMANN, 1980) and compared to a more controlled breathing pattern (HEYDER, 1984), the existence of reproducible differences related to the breathing pattern was evident. Greater than 95% of the variation in the data was explained in each of the investigator-specific logistic analyses. For small particles, spontaneous breathing yields a greater average TB deposition of particles, while for larger particles the converse holds. When the digitized data were plotted, intersubject variability for TB deposition with spontaneous breathing was greater than the mean difference between the two breathing patterns. This mitigates concern about which

breathing pattern is more appropriate for estimating deposition in man following exposure to ambient airborne contaminants, and a logistic model based upon the combined TB data of all investigators was used in all subsequent analyses to represent "population averages". The combined TB data yielded a logistic model explaining approximately 96% of the variation in the data with model parameters being $\alpha = 3.49$, $\beta = -4.84$.

Using the ET and TB logistic model deposition curves and the data of Table 1 for the fraction of air passing through the nose versus the mouth at a given level of ventilation, we examined ET, TB, and thoracic deposition over a range of minute ventilations from resting respiration to heavy exercise for normal augmenters and mouth breathers. Breathing frequencies and tidal volumes for the minute ventilations studied were based upon data from Table 120 of the 1975 International Commission on Radiological Protection (ICRP) report. Minute ventilation curves for ET deposition are shown in Figure 1. For normal augmenters (Panel A, Fig. 1), deposition curves become distinct, shifting to the right for larger values of $\rho d^2 Q$, only when $\dot{V}_E$ exceeds the oronasal switching point (~ 35 $Lmin^{-1}$). However, for mouth breathers, since there is an oral component of airflow at all minute ventilations (see Table 1), the ET deposition curves for this group are all distinct (Panel B, Fig. 1).

From the ET deposition values associated with the various particulate sizes used to calculate $\rho d^2 Q$, there is less deposition in the head at any given size of particle for mouth breathers compared to normal augmenters for a $\dot{V}_E$ of 10 $Lmin^{-1}$ (normal respiration). As $\dot{V}_E$ increases from 10 to 30 $Lmin^{-1}$, ET deposition increases for a given particulate size in normal augmenters. Deposition decreases at 40 $Lmin^{-1}$ due to switching to oronasal breathing before increasing again at higher $\dot{V}_E$ values. However,

since mouth breathers have an oral component of airflow even at normal respiration, ET deposition is essentially a nondecreasing function at all particulate sizes.

Tracheobronchial and thoracic deposition curves are shown in Figures 2 and 3, respectively. For normal augmenters, the peaks of the TB deposition curves shift towards lower particulate sizes for $\dot{V}_E$ less than the oronasal switching point. Just beyond the oronasal switching point, there is a 2- to 4-fold increase in the deposition of particles $\geq$ 5 μm D_{ae} (Fig. 2, Panel A). In contrast, for mouth breathers, there is less variability in the particulate sizes associated with the peaks in the TB deposition curves, and TB deposition basically decreases as $\dot{V}_E$ increases (Fig. 2, Panel B).

In both normal augmenters and mouth breathers, thoracic deposition curves (Fig. 3) reflect the large contribution (about ½) of P deposition of particles $\leq$ 4 μm D_{ae} for low minute ventilations. At higher $\dot{V}_E$, the contribution of P deposition of $\leq$ 4 μm D_{ae} particles to thoracic deposition falls to about 1/3. Although P deposition decreases for larger particles, the pattern of change, as a function of $\dot{V}_E$, is not easily discerned. Independent of $\dot{V}_E$, P deposition is negligible for 12 μm D_{ae} or larger particles.

With minute ventilations of 40 or 60 $Lmin^{-1}$, there is not much difference between normal augmenters and mouth breathers in the thoracic deposition for particulate sizes beyond the peak of the deposition curve. For $\dot{V}_E$ less than the oronasal switching point, deposition is substantially lower in normal augmenters compared to mouth breathers. As $\dot{V}_E$ increases, thoracic deposition for normal augmenters initially decreases for a given particulate size, increases through the oronasal switching point, and then decreases. For mouth breathers, however, there are minimal changes in

deposition at lower ventilation rates with monotonic declines in deposition as $\dot{V}_E$ increases beyond 30 $Lmin^{-1}$.

From these and other results, it can be deduced that regional respiratory tract deposition of insoluble particles in man is a complex function of breathing route, ventilatory level, and particulate physical and aerodynamic properties. Our analyses demonstrate that the activity level of the exposed population should be taken into account to assess the potential health consequences from ambient or workplace exposures.

Acknowledgment New data from New York University were part of a research program (ES00881) and a center program (ES00260) from the National Institute of Environmental Health Sciences.

Disclaimer: This report has been reviewed by the Health Effects Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

References

1. Chan, T.L. and Lippmann, M. (1980). Experimental measurements and empirical modelling of the regional deposition of inhaled particles in humans. Am. Ind. Hyg. Assoc. J. 41:399-409.
2. Environmental Protection Agency (1982). Respiratory tract deposition and fate of inhaled aerosols and sulfur dioxide. In: Air Quality Criteria for Particulate Matter and Sulfur Oxides Vol. III, EPA-600/8-22-019. ECAO, EPA, Research Triangle Park, NC.
3. Foord, N., Black, A., and Walsh, M. (1978). Regional deposition of 2.5-7.5 μm diameter inhaled particles in healthy male non-smokers. J. Aerosol Sci. 9:343-357.
4. Heyder, J. (1984). Studies of particle deposition and clearance in humans, Symposium of the Federal Health Office, Instiutute of Drugs, Berlin, April 2-4.
5. International Commission on Radiological Protection (1975). Report of the Task Group on Reference Man. ICRP Publication 23. Oxford, Pergamon Press.
6. Lippmann, M. (1970). Deposition and clearance of inhaled particles in the human nose. Ann. Otol. Rhinol. Laryngol. 79:519-528.
7. Lippmann, M. (1977). Regional deposition of particles in the human respiratory tract, In: Handbook of Physiology - Reaction to Environmental Agents (Edited by D.H.K. Lee et al.), pp. 213-232. The American Physiological Society, Bethesda, MD.

8. Martonen, T.B. and Miller, F.J. (in press). Dosimetry and species sensitivity: key factors in hazard evaluation using animal exposure data. J. Aerosol Sci. (13th Annual Conference of the Gesellschaft für Aerosolforschung, Garmisch-Partenkirchen, FRG, 1985).

9. Niinimaa, V., Cole, P., Mintz, S., and Shephard, R.J. (1981). Oronasal distribution of respiratory airflow. Respir. Physiol. 43:69-75.

10. Swift, D.L. and Proctor, D.F. (1982). Human respiratory deposition of particles during oronasal breathing,. Atmos. Environ. 16:2279-2282.

11. Yu, C.P. (1978) A two component theory of aerosol deposition in human lung airways. Bull. Math. Biol. 40:693-706.

12. Yu, C.P., Diu, C.K., and Soong, T.T. (1981). Statistical analysis of aerosol deposition in nose and mouth. Am. Ind. Hyg. Assoc. J. 42:726-733.

Table 1. Proportionality of Airflow Between the Nose and Mouth as a Function of Minute Ventilation in Normal Augmenters and Mouth Breathers.†

		Minute Ventilation ($Lmin^{-1}$)				
		10	20	30	40	60
Normal Augmenters	Nose	1.00	1.00	1.00	.53	.45
	Mouth	.00	.00	.00	.47	.55
Mouth Breathers	Nose	.70	.47	.40	.34	.30
	Mouth	.30	.53	.60	.66	.70

†Data derived from Fig. 2 of NIINIMAA et. al. (1981).

Figure Legends

Figure 1. Extrathoracic deposition of particles for normal augmenters (Panel A) and mouth breathers (Panel B) as a function of an impaction parameter for minute ventilation, $\dot{V}_E$, ranging from a resting level (10 $Lmin^{-1}$) to heavy exercise (60 $Lmin^{-1}$).

Figure 2. Tracheobronchial deposition of particles for normal augmenters (Panel A) and mouth breathers (Panel B) as a function of aerodynamic particulate diameter for minute ventilation, $\dot{V}_E$, ranging from a resting level (10 $Lmin^{-1}$) to heavy exercise (60 $Lmin^{-1}$).

Figure 3. Thoracic deposition of particles for normal augmenters (Panel A) and mouth breathers (Panel B) as a function of aerodynamic particulate diameter for minute ventilation, $\dot{V}_E$, ranging from a resting level (10 $Lmin^{-1}$) to heavy exercise (60 $Lmin^{-1}$).

FIGURE 1.

Extrathoracic Deposition

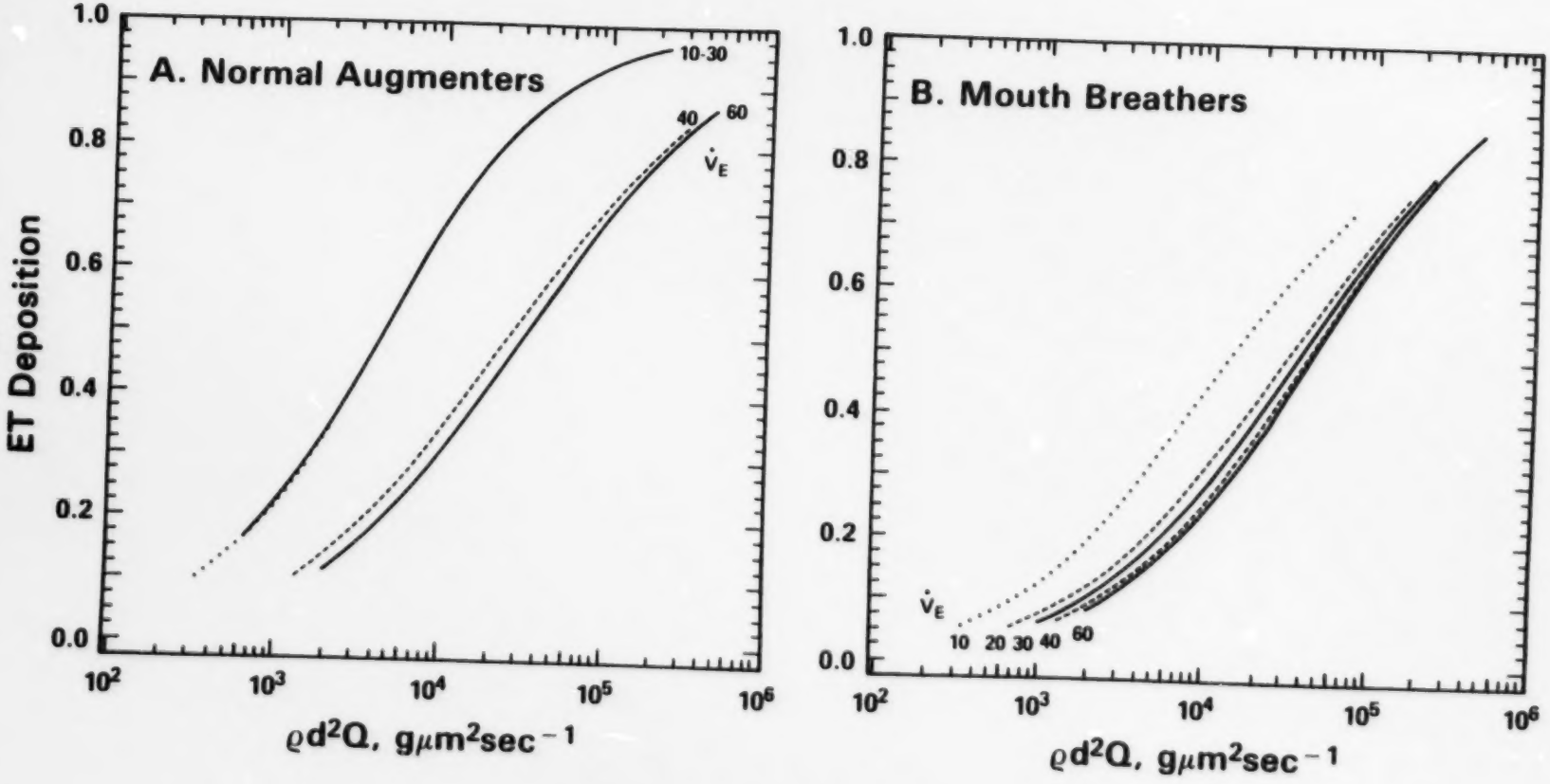

FIGURE 2.

FIG. 2

Tracheobronchial Deposition

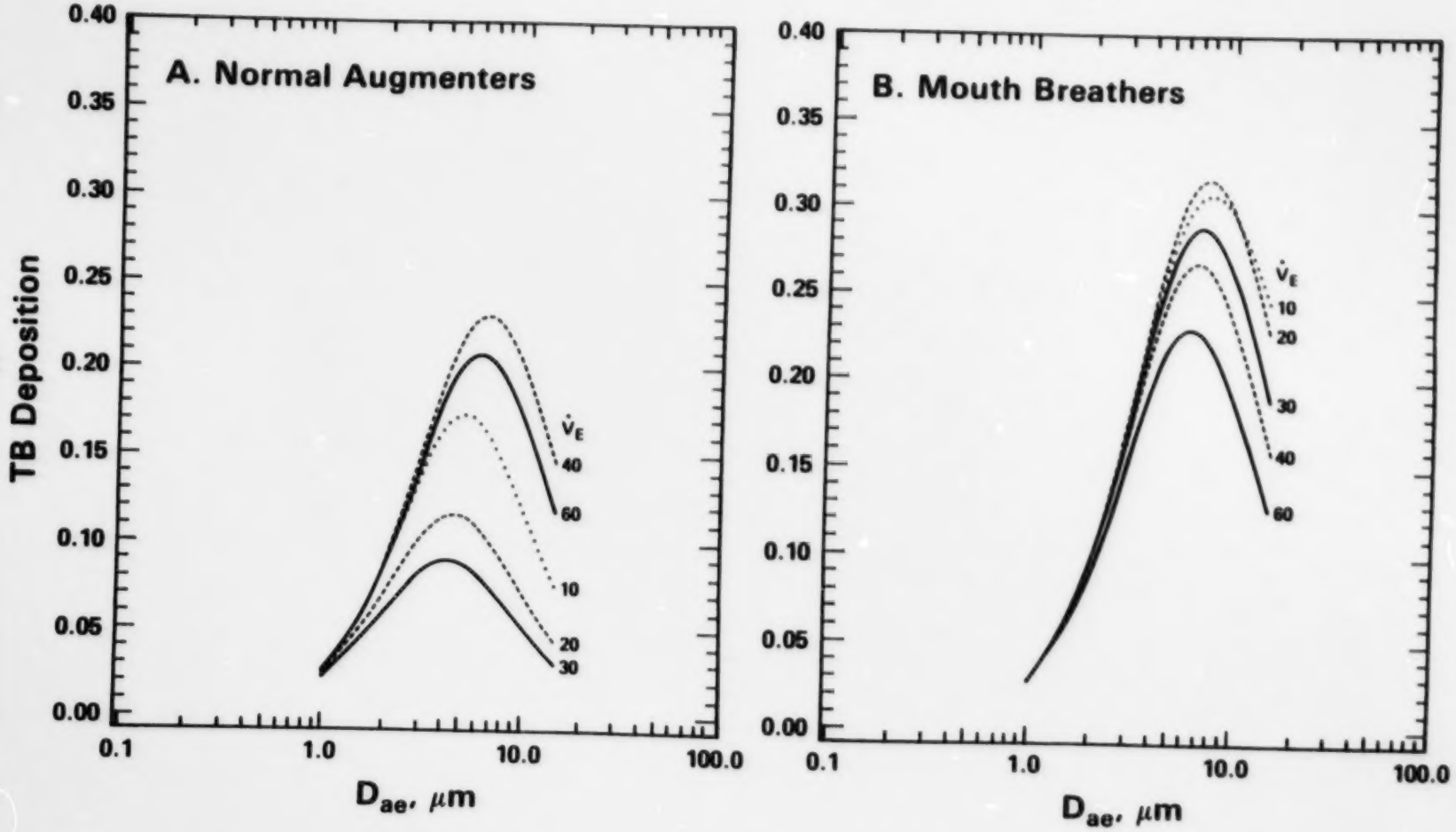

FIGURE 3.

Thoracic Deposition